

HAMLET - Hypstar-based Angular Measurements for hyperspectral Earth-observation validation

Emanuele Spirito¹, Gabriele Candiani¹, Lorenzo Parigi^{1,2}, Mirco Boschetti¹, Vittorio Brando³, Monica Pepe¹

¹ CNR-IREA, Milan, Italy - (spirito.e, candiani.g, boschetti.m, pepe.m)@irea.cnr.it

² Sapienza Università di Roma, Rome, Italy - parigi.l@irea.cnr.it

³ CNR-ISMAR, Rome, Italy - vittorio.brand@cnr.it

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Abstract

The advent of hyperspectral missions such as DESIS, EMIT, PRISMA and EnMAP increases the need for robust calibration and validation frameworks. While Pseudo Invariant Calibration Sites support vicarious calibration, validation of L2 products requires Fiducial Reference Measurements over real, diverse landscapes. ESA's HYPERNETS initiative addresses this goal by deploying continuous, automated spectroradiometric measurements across multiple sites. In this context, agricultural targets pose major challenges due to strong seasonal dynamics, non-Lambertian behavior, and viewing geometry effects, further complicated by off-nadir acquisitions. To analyze such targets, two crop seasons of HYPSTAR®-XR multi-angular spectroradiometer (ranging from 380 nm up to 1680 nm) and satellite data were collected at the Jolanda di Savoia agricultural site, located in northern Italy (JSIT). Constrained match-ups between satellite and JSIT reflectances were analysed through HAMLET, an ad-hoc R package developed to support improved validation practices for hyperspectral reflectance products in complex targets.

1. Introduction

The new era of hyperspectral space borne missions - including, NASA-EMIT, ASI-PRISMA, and DLR-DESI and EnMAP - has significantly increased the demand for robust calibration and validation frameworks capable of ensuring the accuracy and consistency of derived products. While Pseudo-Invariant Calibration Sites (PICS) provide a well-established basis for vicarious radiometric calibration, the validation of Level-2 products requires high-quality Fiducial Reference Measurements (FRM) collected over representative and diverse natural surfaces. This is needed for properly estimate the uncertainties of L2 Bottom Of Atmosphere (BOA) Reflectance products for different targets to enable propagation of such uncertainties to L3 products, as obtained from different processors, designed for different purposes. This uncertainty propagation is particularly important when Earth Observation (EO) products are then assimilated in different frameworks. This validation needs are the basis for the establishment of the HYPERNETS initiative, which is a European research and operational network designed to provide high-quality Fiducial Reference Measurements (FRM) for the calibration and validation of optical satellite missions (Ruddick et al., 2024). It was initially developed through the EU Horizon 2020 project HYPERNETS and is now supported by ESA and international partners. The initiative is based on a network of automated hyperspectral radiometers (HYPSTAR® systems) installed at representative land and water sites around the world. These instruments continuously measure surface reflectance with high spectral resolution over the 380-1680 nm range, providing traceable and uncertainty-characterized observations that can be directly compared with satellite products, provided that the geometrical setups is correctly taken into account. As an example, both ASI-PRISMA and DLR-EnMAP missions have established validation site networks (Cogliati et al., 2021) (Pato et al., 2025), considering different targets, which are connected to main EO data exploitation domains (e.g. agriculture, water, environmental monitoring, climate change), and

this could take advantage of the HYPERNETS initiative also in the perspective of the forthcoming missions, such as ESA-CHIME (Nieke et al., 2023) and NASA-EAGLE, formerly known as SBG (Turpie et al., 2023). Within validation sites for hyperspectral L1/L2 products, agricultural environments represent a particularly challenging class of targets due to: i) pronounced seasonal variability of crops, resulting in high changes in spectral response in time, as due to growing stages; ii) complex canopy structure resulting in non-Lambertian reflectance behavior, and strong dependencies on illumination and observation geometry. These challenges become even more critical for hyperspectral missions operating with off-nadir viewing configurations, such as PRISMA, EMIT and EnMAP. To investigate these effects a dedicated processing and analysis tool - namely HAMLET - Hypstar-based Angular Measurements for hyperspectral Earth-observation validation - was developed to generate constrained satellite-to-ground match-ups and support detailed investigations of angular effects and temporal variability of surfaces. The objective of HAMLET is to create an automated robust match-up tool to enable the investigation of seasonal, viewing geometry and bidirectional reflectance (BRDF) effects for uncertainty estimation of BOA reflectance products, mainly applied to the validation of satellite mission over cropland surfaces, for proper uncertainty propagation in higher level products (e.g. Leaf Area Index, crop traits such as Chlorophyll and Nitrogen contents). To demonstrate HAMLET capabilities and crop targets related problems, two complete crop seasons of HYPSTAR®-XR multi-angular measurements (covering wavelengths up to 1680 nm) were acquired at the JSIT (Jolanda di Savoia, Italy) agricultural validation site and analyzed together with corresponding satellite observations. The resulting framework contributes to more reliable validation methodologies for hyperspectral surface reflectance products over complex and dynamically changing agricultural landscapes.

2. Materials and Methods

2.1 Study area

The JSIT HYPERNETS station is located in the Bonifiche Ferraresi S.p.A. farm (44°53'N; 11°59'E) in Jolanda di Savoia, near Ferrara, in Italy's Po Valley (figure 1). The farm total area encompasses approximately 3800 ha, with a diversified crop production focused on both human consumption and animal feeding. The area was formerly a marshland which underwent extensive reclamation efforts during the late 19th century. The soil, which is characterized by high fertility, is predominantly composed of silty-clay or silty-clay loam. It is distinguished by the presence of numerous buried paleochannels, which are indicative of its former coastal environment. Such a condition generates a substantial within-field spatial pattern as a consequence of plant-soil interactions. The HYPSTAR®-XR radiometer is located within a crop field of approximately 20 ha and is positioned in a spectrally homogeneous area measuring 100 m × 100 m. This area corresponds to a 3 × 3 satellite pixel window for sensors with a spatial resolution of 30 m, ensuring representative satellite-to-ground comparisons. (figure 1). This configuration has been chosen in compliance with the principles and test-site best practises indicated by QA4EO (Quality Assurance Framework for Earth Observation) of the Committee on Earth Observing Satellite (CEOS) (Woolliams et al., 2025). This site is included in the PRISMA mission scientific validation network (PRISCAV) and in the EnMAP foreground mission. It has been object of different field campaigns to acquire ground data contemporary to satellite observation in the frame of national and international research project devoted to remote sensing data CAL/VAL activities and crop traits estimation.

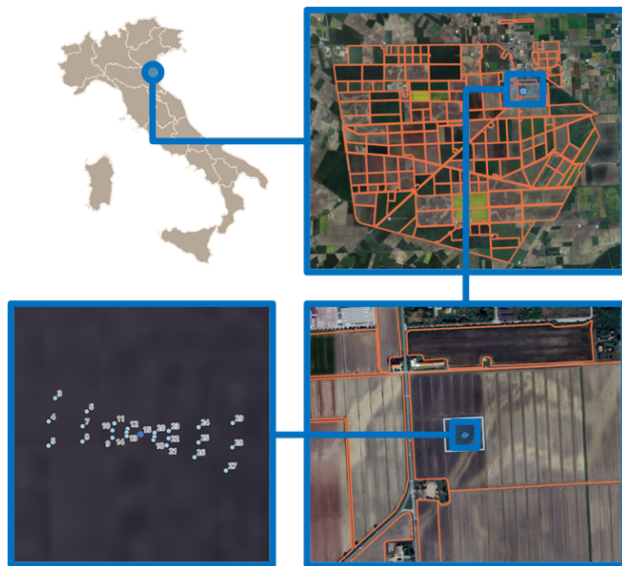


Figure 1. Study area (Bonifiche Ferraresi S.p.A. farm) overview, JSIT location within the field and configuration of Hypstar measurements.

2.2 Materials

2.2.1 In-situ data The JSIT radiometer is deployed on a 2-meter-long arm attached to a 10-meter-high mast. The mast is fixed to a metal plate embedded in an underground concrete block with a volume of approximately 5 m³ (figure 3a). The instrument collects radiance data between 380-1680 nm, at vari-

ous viewing geometries and send it to a central server for quality control and processing. The HYPSTAR®-XR (Kuusk et al., 2024) includes a VNIR sensor (1330 channels, range 380 -1000 nm, 3 nm FWHM), and a SWIR sensor (220 channels up to 1680nm, 10nm FWHM). The system is also equipped with an RGB camera allowing for checking the target and sky conditions. All the products have associated uncertainties, propagated using the CoMet toolkit. (De Vis et al., 2024) (www.comet-toolkit.org). Data suitable for satellite validation are available at <https://doi.org/10.5281/zenodo.17619560>. In figure 2 to give an insight on all the 27 viewing geometries, the shootings of HYPSTAR RGB camera data collection of the target is shown.

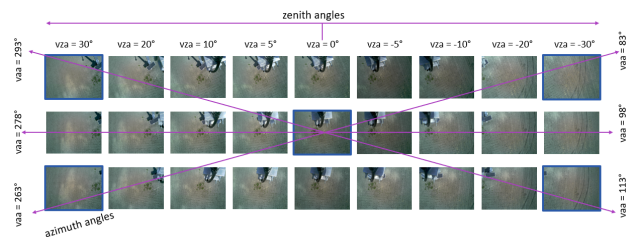


Figure 2. HYPSTAR radiometer's acquisition geometries.

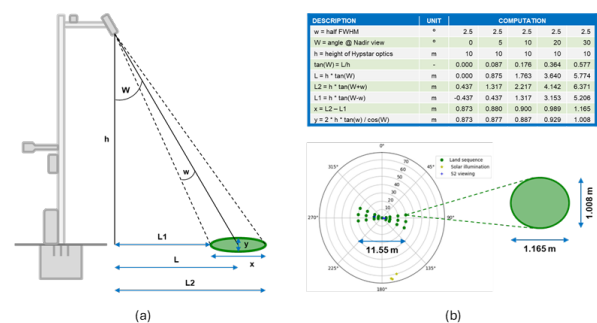


Figure 3. JSIT structure (a) and polar plot showing the typical land protocol viewing geometries for the LANDHYPERNET network (b). The table on the top right shows the computation used to determine the minor and major diagonal of the oval footprint for each zenith angle (0°, 5°, 10°, 20°, 30°).

The Landhypernet sequence protocol encompasses six viewing azimuth angles (VAA = 83°, 98°, 113°, 263°, 278°, and 293°) and five viewing zenith angles (VZA = 0°, 5°, 10°, 20°, and 30°) for a total of 27 measurements. Given the specified viewing geometry, the aggregate footprint, as determined by the sum of all pertinent measurements, spans approximately 12 meters. The single measurement at 30° of VZA is an oval with two diameters measuring approximately 1 m and 1.2 m (figure 3b). The infrastructure is also equipped with an eddy covariance system, provided by CNR-IBE (<https://www.ibe.cnr.it/>). Additional information regarding each deployment period, including specific crop types, can be found at https://landhypernet.org.uk/site_descriptions/JSIT. The JSIT radiometer acquisitions occur every 30 minutes, starting from UTC time 05:00:00 up to UTC time 16:30:00. After a sequence is acquired, the processing of the acquisition goes up to Level-2 only if quality checks are passed. An example of quality check is the cloudy acquisition filter: when the acquisition is made in clear-sky conditions, nearly without any cloud contamination, the sun irradiance before and after each sequence of acquisitions should not change much. The HYPERNETS framework delivers an HDF5 file relative to each acquisition sequence.

From that dataframe, HAMLET tool imports the needed data and organise the dataframe according to the following structure: i) acquisition date [Y-M-D]; ii) acquisition starting time [H:M:S]; iii) viewing zenith angle [deg]; iv) viewing azimuth angle [deg]; v) sun zenith angle [deg]; vi) sun azimuth angle [deg]; vii) HYPSTAR acquisition band number; viii) mean reflectance for 10 repeated measurements; ix) acquisition spectral wavelength [nm]; x) standard deviation of reflectance for 10 repeated measurements; xi) HYPERNETS site name.

2.2.2 Spaceborn data collection The tool, in its current implementation, is product-ready for creating match-ups between HYPERNETS in-situ data and remote sensed Level-2 processed data acquired from ASI-PRISMA, DLR-EnMAP, and Copernicus-Sentinel2 data.

In order to demonstrate the capability of the tool through examples, the satellite images listed in table 1 have been used. Each of them covers in its footprint the JSIT location described in section 2.1.

Satellite	Date (Y/M/D)	Time (H:M:S)
PRISMA	2024/11/13	10:10:57
EnMAP	2025/04/10	10:40:34
PRISMA	2025/04/24	10:04:26
PRISMA	2025/08/01	10:10:52
Sentinel-2	2025/04/24	10:18:37
Sentinel-2	2024/11/13	10:18:23

Table 1. Satellite images data used for tool examples

Compliance to the HYPSTAR data structure described in section 2.2.1 is accomplished by creating a similar data structure for spaceborne data: i) acquisition date [Y-M-D]; ii) acquisition start time [H:M:S]; iii) viewing zenith angle [deg]; iv) viewing azimuth angle [deg]; v) sun zenith angle [deg]; vi) sun azimuth angle [deg]; vii) satellite acquisition band number; viii) mean reflectance for N closest pixels around the HYPSTAR sensor location; ix) acquisition spectral wavelength [nm]; x) standard deviation of reflectance for N closest pixels around the HYPSTAR sensor location; xi) satellite name. The N parameter can be chosen by the user. When comparing different satellites against JSIT, the user is suggested to choose proper N values according to the given spatial resolution of the different sensors Ground Sampling Distances, in order to include the same footprint inside the datasets.

2.3 Methodology

HAMLET is designed and implemented as an open-source tool that enables users to generate custom matchups between quality-checked HYPSTAR®-XR L2B surface reflectance data and hyperspectral satellite L2 products, but also multispectral configurations, such as Sentinel-2, are taken in consideration. HYPSTAR®-XR data are quality controlled and spectrally resampled to the target sensor using native or derived from the FWHM and band centres, spectral response functions (SRF). Satellite observations are averaged over cloud-free acquisitions within a user-defined temporal window across the four pixels closest to the instrument location. Matchups account for satellite–ground–sun geometry, by comparing observations acquired under the closest daytime conditions (equiv. solar zenith angle - SZA) and viewing angle or by using a (weighted) average over a daytime range (equiv. SZA) and viewing angle range centered on the satellite geometry configuration. After each analysis, the tool automatically generates a report including matchup and polar plots to visually assess zenithal and azimuthal variability relative to a given satellite acquisition. In addition to mean values,

temporal and viewing-angle standard deviations are computed to quantify variability across different geometries. For temporally homogeneous field conditions, intrinsic variability is estimated from repeated acquisitions under fixed ground station–sun geometry. The overall objective is to characterize random and systematic uncertainties in ground-based measurements.

2.3.1 User configuration Given that a perfect alignment between the HYPSTAR and satellite acquisition geometries, together with sun position, is unlikely to occur, the HAMLET user is supposed to make a decision about the way to consider the best FRM set to be used for match-ups. At first glance, this choice may appear straightforward; however, it is far from trivial. Identifying the ground-based acquisition that is closest to the satellite observation in both time and viewing geometry is often challenging. While the satellite overpass can be considered nearly instantaneous, a complete HYPSTAR acquisition cycle requires approximately 30 minutes to perform all 27 measurements, resulting in temporal and angular offsets that must be carefully accounted for. So that, in order to generate customized match-ups, HAMLET requires the user to specify the following configuration settings:

- local repositories paths;
- `start_date` and `end_date`;
- which satellite to compare HYPERNETS site acquisitions to (currently choosing among PRISMA, EnMAP and Sentinel-2);
- the `number_closest_pixels` to the HYPERNETS acquisition site. The default configuration is optimized for the JSIT site (i.e. a 60m square around the JSIT tower);
- the `delVZA` and `delVAA` parameters, i.e. which HYPSTAR viewing angles are to be ignored. Usually the mast base-moment (at $VZA = 0^\circ$) is always removed but also any plots in the cropfield that the user wants to exclude from match-ups;
- the `only_same_date` parameter, i.e. whether the user wants to compare satellite and HYPSTAR acquisitions also of different dates (always keeping the closest date);
- the `time_or_sun_angle` parameter, i.e. whether the user wants to aggregate HYPERNETS data speaking in terms of time or sun position in the sky;
- the `just_closest_time_or_sun_angle` parameter, i.e. whether the user wants to matchup either only the closest time/sun-angle HYPERNETS data to the satellite acquisition time/sun-angle or all the HYPERNETS data in a time/sun-angle window centered around the satellite acquisition;
- the `range_time_or_sun_angle` parameter, i.e. how large the time/sun-angle window has to be, respectively in terms of hours/degrees;
- the `just_closest_view_angle` parameter, i.e. similar to `just_closest_time_or_sun_angle` but for the viewing angles;
- the `range_view_angle` parameter, i.e. similar to `range_time_or_sun_angle` but for the viewing angles;
- the `weighted_mean` parameter, i.e. whether the user wants to perform all the aggregations in time and angles using a simply or weighted mean.

2.3.2 Workflow The tool will first import the data from local repositories, both quality controlled HYPERNETS HYPSTAR@-XR L2B surface reflectance data and the satellite L2-like data inside the chosen dates. Satellite observations are then averaged across the N pixels closest to the instrument location, filtering out the cloud contaminated pixels.

The matchup phase includes the following steps:

1. HYPERNETS data are filtered out of unwanted viewing angles;
2. HYPERNETS data are spectrally resampled to the target sensor using the related spectral response functions (SRF) either native or derived from the FWHM and band centres;
3. HYPERNETS and satellite data are joined by dates;
4. HYPERNETS and satellite data are joined by time or sun angles. Depending on the user's setup this can result in a matchup between the satellite and the closest HYPSTAR daytime/sun-angle acquisition or a matchup between the satellite and the (weighted) average of all the HYPSTAR daytime/sun-angle acquisitions in a window centered on the satellite acquisition;
5. HYPERNETS and satellite data are joined by viewing angles. Again, the user can choose to get the matchup with the closest or the (weighted) average acquisition geometry.

At the end of the matchup phase the user gets a data structure that is the both user's intended and proper join of the data structures of HYPERNETS and satellite found in the sections 2.2.1 and 2.2.2, that can be referred to as matchup, since it's a dataframe structure containing wavelength, reference reflectance and target reflectance, together with a quantification of our confidence on those reflectances that can be reported as uncertainty and standard deviation. The tool also offers a column, i.e. operations, dedicated to the history of all the processing done over the HYPERNETS data to get to the final matchup and a column, i.e. number_data_in_window, to quantify how many HYPERNETS data has fallen in the averaging window chosen by the user, set to 1 in case the user has chosen the closest geometry matchup.

2.3.3 Tool visual outputs After each analysis, the tool automatically generates a report including a set of predefined plots that summarise the matchup condition and the angular variability. The *polar plots* allow the user to visually assess zenithal and azimuthal variability relative to a given satellite acquisition. They are built choosing among the satellite band channels the one whose wavelength is closer to 900 nm and, using polar coordinates to distinguish viewing zenithal and azimuthal angles, they display through a color gradient how much the satellite surface reflectance differs from the HYPERNETS surface reflectance. The *ribbon plots* show along all wavelengths the values of the satellite and the HYPERNETS average surface reflectance spectra outcoming HAMLET matchup aggregation, together with their standard deviations represented as halos centered on respective average. Moreover, the *rainbow plots* represent the scatterplots among the satellite and HYPERNETS surface reflectances, visualized using a gradient of visible colours for the visible bands and a grey-scale for the infrared ones. In addition, the *relative error plots* are generated showing for each wavelengths how much the satellite surface reflectance deviates from the HYPERNETS surface reflectance in percentage.

Together with those plots, the user also obtains the CSV file containing the final matchup dataframe described in section 2.3.2 to create further plots and analysis not already included in the default visual outputs.

2.3.4 Error measures propagation The uncertainty and standard deviation are critical error measures when trying to assess the variability across different geometries. For temporally homogeneous field conditions, intrinsic variability is estimated from repeated acquisitions under fixed ground station–sun geometry. The propagation of standard deviation is performed through the following equation:

$$\sigma_{\text{average}} = \frac{1}{N} \sqrt{\sum_i [\sigma_i^2 + N * \sigma^2(R)]} \quad (1)$$

where σ_i is the intrinsic standard deviation for the i -th measure, N is the number of measures and $\sigma^2(R)$ is the variance of the surface reflectance average values. The standard deviation is first imported from HDF5 computed for repeated measurements with the same geometry. Then alongside each aggregation step performed by HAMLET there is the need of propagating that standard deviation. The authors instead of propagating the standard deviation with the basic formula:

$$\sigma_{\text{average}} = \frac{1}{N} \sqrt{\sum_i \sigma_i^2} \quad (2)$$

wanted to keep also the mean value variability. For this reason another term has been added in equation 1. The weight factor of that term addresses the problem of balanced standard deviation: in the limit where the intrinsic standard deviation are small compared to the standard deviation of average values, the total standard deviation should behave as a classic standard deviation, whilst in the opposite case the total standard deviation should tend to the propagation of intrinsic standard deviation as in equation 2.

2.3.5 Importance of angles filtering In figure 2 the HYPSTAR mast is clearly visible, especially when the zenith angle is close to zero. Keeping this data inside the set of valid HYPSTAR data can introduce contamination related to the base of the mast in the spectral measurements. Moreover, natural crop dynamics may hamper the target homogeneity, making advisable to use only some of the plots; in this case the user may want to focus only over those specific plots. For those reasons, the tool allows the user to filter out in advance some measurements according to given sets of zenith or azimuth angles. In the standard workflow presented in this work any data collected at nadir is discarded.

3. Results and Discussion

Preliminary experiments were performed to assess both the suitability of HAMLET for match-up analysis and the interpretability of its outputs under different target conditions and for different sensors; to analyse reflectance differences under different match-up settings; and to investigate the target–acquisition dynamics.

3.1 Agricultural target dynamics

As a first experiment to understand variability in L2 uncertainty induced by the crop dynamics two very different conditions in

JSIT farmland were considered: bare soil and full vegetative phase of crop. Bare soil conditions (fig. 4) are illustrated using match-ups from a PRISMA acquired on November 13th 2024, one day after soil tillage. Vegetative phase conditions, of winter wheat, (fig. 5), are illustrated through match-up of an EnMAP acquired on April 10th 2025.

In the case of bare soil conditions, referring to 4, all HYPSTAR®-XR angular measurements within the temporal window closer to satellite overpass are considered. Due to the low signal level, bare soil targets are particularly useful for investigating issues related to low signal-to-noise conditions and adjacency effects in atmospheric correction. In addition, the low solar elevation angle likely contributes to increase the relative error (figure 4, right panel). In vegetative phase case, the target presents higher values along the whole spectrum and a greater spatial homogeneity, as testified by the lower EnMAP standard deviation in the ribbon plot (Fig. 5 left panel). When analysing the ribbon plots it seems that both satellites performances are good (excluding the atmospheric absorption bands), independently from the target dynamics, but looking into more details on relative errors there are differences that need a disentangling if are depending on the sensor or (also) on the target dynamics. For that reason a comparison with 2 PRISMA images on the two extreme conditions - bare soil on November 2024, and winter wheat in vegetative phase April 2025 - were considered, to focus only on the seasonal dynamics, independently from the sensor. Considering the left panel of figure 6, the relative errors are different for the two conditions in the visible (scatter plot on the right panel is indicative), and while the overall behaviour is similar in the infrared, looking at the values - as highlighted by purple arrows - with the change in dates the relative error sign changes, and it is closer to zero for the bare soil condition. This proves that even with the same satellite sensor the target cover conditions affected the validation results significantly at the same site. Considering the right panel of figure 6, shows that in the visible range the satellite surface reflectances are always lower than the HYPSTAR ones, which doesn't change with dates, even if the differences (scatterplots) are not constant. To further investigate this seasonality effect, and try to understand how much it is connected to the hyperspectral missions' at hand (narrow bands and off-nadir viewing angle), the same comparison was made using Sentinel-2 (multispectral) satellite with very close overpass times with PRISMA on the same ones clear-sky days analyzed before (24th April 2025 and 13th November 2024). This is to verify if there is a similar behaviour in the relative error between satellite and in-situ reference data, which could be connected to seasonality. Figure 7 show the match-up outputs for Sentinel-2. Also in this case the sign of relative error changes from positive biases in vegetation phase to negative ones in bare soil (left panel), again the visible bands perform differently in the two conditions, as also highlighted by the circles in the scatter plots (right panel). Additional cases - not presented here - under similar conditions were analysed, highlighting the strong need for ancillary field data, including vegetation status, timing of agro-practices and all crop-related events (e.g. lodging) to support robust interpretation of match-up results.

3.2 Angular variability and importance of configuration

As aforementioned the angular match-up choices regarding angles are not straightforward and could lead at different results. As an illustrative example, figure 8 shows the polar plot of a match-up between a PRISMA image and all HYPSTAR

viewing geometries acquired under bare-soil conditions in early August, in the case when the HYPSTAR acquisition sequence selected for the comparison is the one with the smallest temporal offset from the PRISMA overpass. For the chosen date (August 1st 2025) in a wheat field, the crop was already harvested and on the field there are crop residues. The plot refers to a full sequence, the one closest to the acquisition time.

Looking at the polar plot of figure 8 it is apparent that the HYPSTAR observations (colored dots) with the closest viewing angles to the ones of the satellite acquisition geometry (black cross) are not the one presenting the lowest bias. Moreover there is a pattern in deviations, smoothly varying, that could be mostly related to BRDF effect and on the relative sun-target-sensor geometry. Having chosen the closest time in creating the match-up this ensures to be in a very similar sun-target geometry. When analyzing the plot, it is clear that the greater the zenith angle is, the more amplified the forward and back scattering effects are, thus creating the red to green pattern when going from left to right in the plot, meaning that it is going closer to the same scattering effect of the satellite (either forward or back). Zenith angles closer to zero have sharp varying effects, probably due to local field inhomogeneity closer to the mast base, that could affect also the comparison for close to nadir acquisitions (such as in the image at hand, with a roll angle of about -5°).

Another example of the differences in match-up results depending on the initial configuration choices in HAMLET is given in figure 9. It refers to the PRISMA image of 24 April 2025 (yellow spectrum); in the top panel represents the HYPSTAR (green) with standard deviation halos. In the top panel the HYPSTAR (green line) measurements' aggregation is obtained by averaging all the sequences in a time window of 2 hours to sandwich the satellite overpass (1h before and 1 hour after) and averaging in a viewing angle window of 360° (all viewing angles). In the bottom panel HYPSTAR measurements aggregation is performed by taking the sequence with closest time to the satellite overpass and then averaging measurements in a viewing angle window of 30° centered on the satellite one. The differences could be easily appreciated in the ribbon plots, and this affects also the related uncertainty metrics. Since, as shown before, the configuration of match-up parameters does effect uncertainty estimation, it is really important to keep track of the match-up parameters together with its outputs in order to ensure consistency and comparability through time and space.

4. Conclusions and Perspectives

To enable automated generation of match-ups between EO products and FRM ground measurements, the HAMLET package was developed as an open-source tool. This is mainly intended for satellite missions independent validation and uncertainty estimates on sites other than PICs. HAMLET allows users to generate custom match-ups between quality-checked L2B surface reflectance data from the HYPERNETS network and hyperspectral (e.g. PRISMA, EnMAP, EMIT, DESIS) or multispectral (e.g. Sentinel-2) satellite BOA reflectance products. Also in consideration of the advent of satellite hyperspectral missions, for which radiometric correction tasks become even more complex. HAMLET characteristics and potentials were showcased for an HYPERNETS agricultural site (namely JSIT) located in the largest farm in Italy. As an agricultural site JSIT presents challenges due to strong seasonal

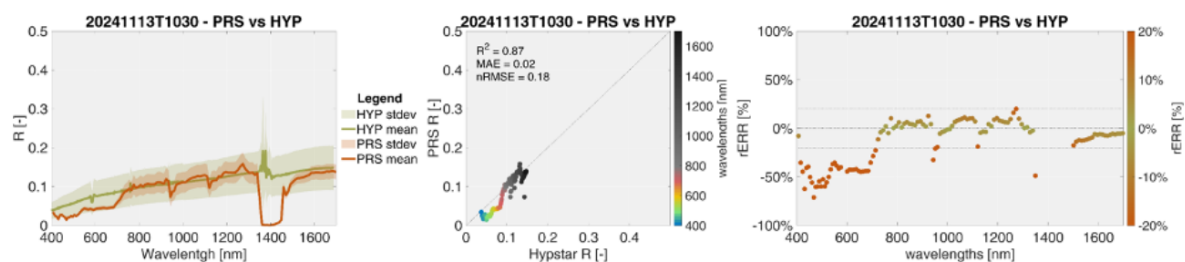


Figure 4. Example of match-up between HYPSTAR and PRISMA acquired on November 13th 2024 on bare soil (day after tillage): on the left panel mean BOA reflectance (for PRISMA standard deviation refers to 4 pixels, for HYPSTAR is the one related to angular variance), in the middle panel scatterplot of reflectance values coloured according to wavelengths, on the right panel relative errors of PRISMA as compared to HYPSTAR according to wavelengths.

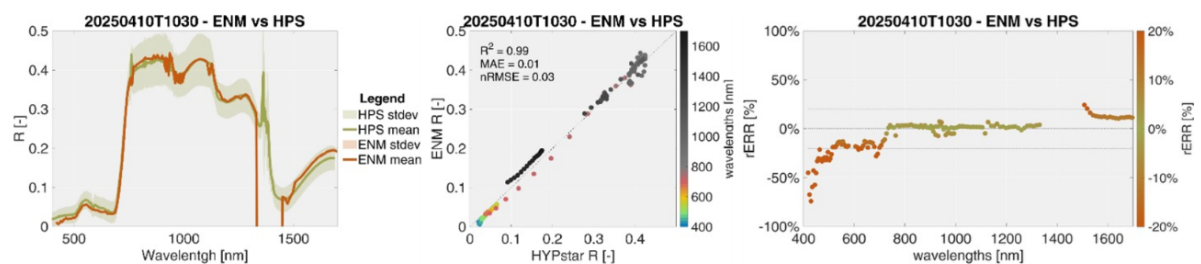


Figure 5. Example of match-up between HYPSTAR and EnMAP on April 10th 2025 on winter wheat in vegetative phase: on the left panel mean BOA reflectances, in the middle panel scatterplot of reflectance values coloured according to wavelengths, on the right panel relative errors of PRISMA as compared to HYPSTAR according to wl.

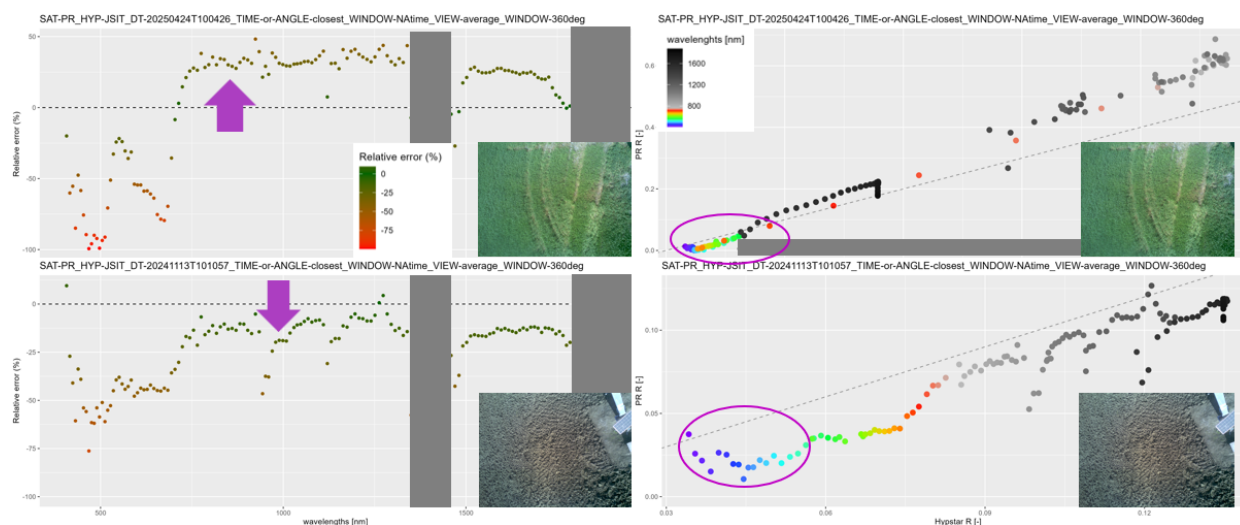


Figure 6. Matchup plots for PRISMA images of 24th April 2025 (top panel) and 13th November 2024 (bottom panel) against the HYPSTAR reference acquisition using closest time and an average viewing window of 360°. The first column shows the relative error plots, while the second column the rainbow plots. For plot details see 2.3.3.

dynamics and non-Lambertian behavior through time and under different viewing geometries. The analysis of PRISMA and EnMAP match-ups collected during the 2025 wheat growing season indicates that relative errors are influenced by seasonal dynamics. This effect is further supported by evidence from concurrent Sentinel-2 acquisitions. This indicates that the knowledge about the field conditions related to crop growth/agricultural practises is relevant to be accounted for. In addition an example of the influence of different match-up con-

figurations on uncertainty representation was presented, underlining that "the closest, the better" for choosing time and angles matches, is not so practical and indicative as it could seem at first, and that different configuration parameters, even though rationale ones, are affecting results. So that the configuration should be considered accurately, since it is not a straightforward task. For the results obtained, it is recommended to always complement match-ups with ancillary data regarding the target dynamics and of the configuration settings. Further HAMLET

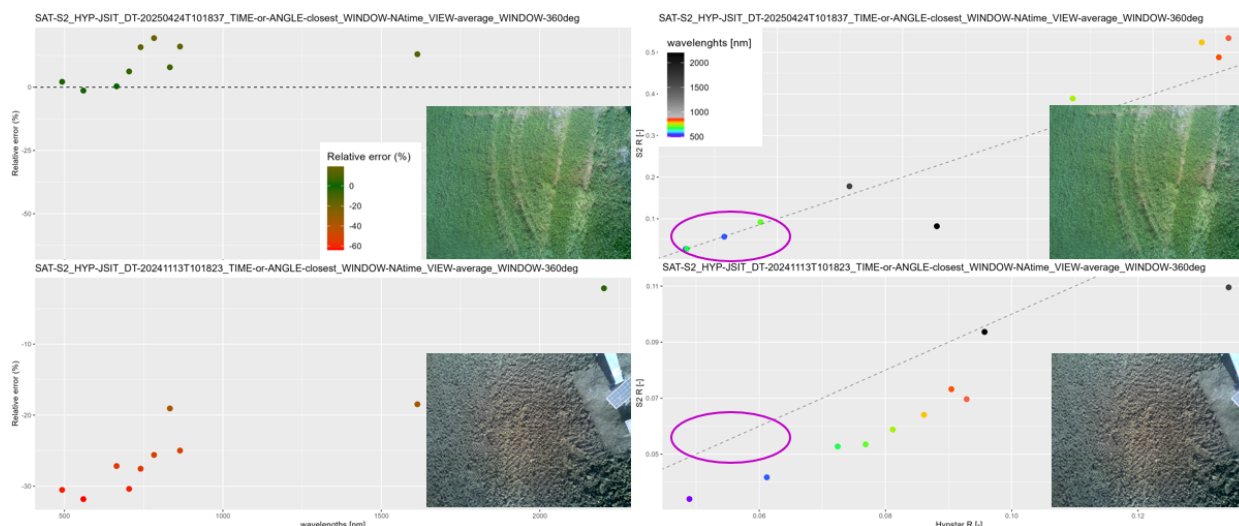


Figure 7. Matchup plots for Sentinel-2 images of 24th April 2025 (left panel) and 13th November 2024 (right panel) against the coeval acquisition of HYPSTAR using closest time and an average viewing window of 360°. The first column shows the relative error plots, while the second column the rainbow plots. For plot details see 2.3.3.

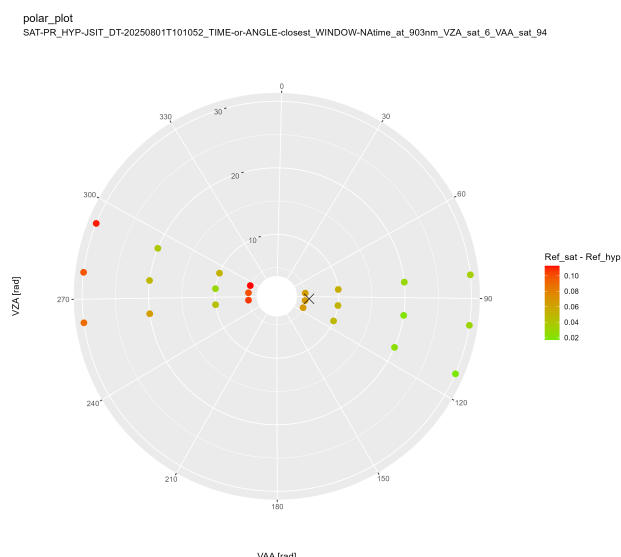


Figure 8. Example of polar plot in match-up between HYPSTAR and PRISMA on August 1st 2025 on harvested field conditions. The satellite viewing geometry is represented with a black cross in the plot, while different HYPSTAR viewing geometries are represented by dots, whose colours vary in a gradient relative to their deviations at 903nm from the satellite surface reflectance.

implementations will consider the inclusion of equivalence ratio (Loew et al., 2017) in the computed metrics; the addition of Immler diagrams to the plotting tools (Gobron et al., 2022); and the possibility to consider QA4EO uncertainty tree diagrams for the propagation of uncertainty up to the match-up phase (Wooliams et al., 2025). As regards HAMLET applications, future work will focus on analyse all PRISMA, EnMAP and EMIT overpasses on JSIT for improving the understanding of measurements sequences to investigate the seasonality effect and to identify optimal angular and temporal configurations for reliable match-ups, and to establish a reference routine for BRDF evaluation. With the collaboration of the network it will be likely demonstrated on other HYPERNETS' sites.

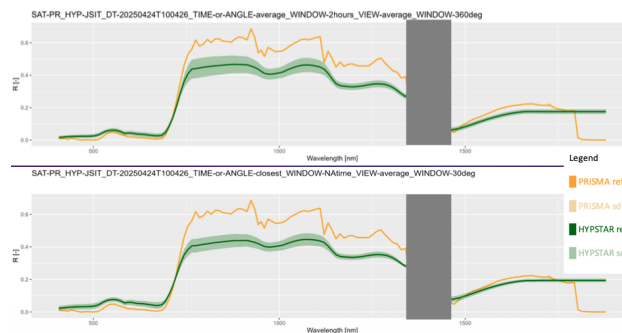


Figure 9. Ribbon plots of PRISMA 20250424 (yellow) against aggregated HYPSTAR (green); standard deviation as halos. Top panel: HYPSTAR aggregation by averaging on 2 hours sandwich on satellite overpass and on all viewing angles. Bottom panel: HYPSTAR aggregation on the sequence with closest time to the overpass and averaging on a viewing angle window of 30° to the satellite one.

4.1 Others

The HAMLET code is free and accessible for the community at <https://github.com/emanuelespiritowork/HAMLET>. The present work refers to the version v0.1.0-alpha.

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